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ORIGINAL RESEARCH ARTICLE

Kinematic Analysis of Hand Movements After Tendon Repair Surgery

A New Assessment Using Drawing Movements

ABSTRACT

Stenekes MW, Nicolai J-PA, Geertzen JHB, Mulder T: Kinematic analysis of hand movements after tendon repair surgery: a new assessment using drawing movements. *Am J Phys Med Rehabil* 2008;87:169–176.

Objective: Although several hand outcome tests exist to judge skill level after hand injury, currently none give insight into how tasks are performed by looking at kinematic parameters. In this article, the clinical value of analyzing kinematic parameters related to the drawing of a triangle on a graphics tablet by healthy subjects and patients with hand injury is discussed.

Design: In a first experiment 10 healthy subjects drew the triangles as accurately as possible at various speeds. In a second experiment, 67 healthy subjects and 12 patients with flexor tendon injury were measured repeatedly.

Results: In the first experiment, the analysis showed a high linear correlation between speed and accuracy for each individual (Pearson correlation coefficient ≥ 0.762 , $P \leq 0.01$). The data led to a formula to standardize deviation for drawing speed, so that different measurements can be compared. In the second experiment, these two measurements correlated well (Pearson correlation coefficient = 0.909, $P < 0.001$), although a learning effect was noticed (5.4% improvement on average). In healthy subjects the dominant hand performed significantly better than the nondominant hand ($P < 0.001$). Patients performed significantly worse with their injured hand after 6 wks of dynamic splinting than did healthy subjects ($P = 0.003$). With their uninjured hand, they performed better than the controls. Six weeks after removal of the splint, no kinematic differences could be discovered between patients and controls.

Conclusion: The results show that kinematic parameters of hand movements may be of additional value for assessing functional recovery from hand injury.

Key Words: Hand Function, Assessment, Finger Flexion, Kinematic Parameters

The treatment of flexor tendon injuries in the hand is focused on full recovery of hand function. A primary aim is regaining undisturbed mechanical qualities of the injured hand. In addition, the recovered patient needs to use his hand in daily tasks, which implies adequate cerebral control. In general, treatment consists of surgical repair of the tendon followed by a 6-wk period of relative immobilization (splinting period).^{1,2} Our clinical observation that many patients reported clumsiness after the splinting period, even when they had perfect mechanical recovery, generated the idea that complaints might be attributable to a disturbed command function. Clumsiness did not only apply to the affected finger but to all immobilized fingers. This hypothesis of changed cerebral function was recently confirmed by a functional brain imaging study by our group, which demonstrated temporary changes in cerebral organization of motor control attributable to relative immobilization of the hand.³ Other groups also report that consequences of peripheral disorders are not limited to the periphery but also lead to central adaptations.⁴

The concept that treatment of tendon lesions in the hand should not only be focused on tendons and joints, but also on cerebral motor control, urges on the development of tools that enable the assessment of disturbed hand function in these conditions.

Several "hand questionnaires" have been developed to measure how patients cope with the functional consequences of hand injury—for example, the Michigan Hand Questionnaire.⁵ Although questionnaires may shed some light on the qualitative recovery, functional tests are more objective measures.^{6,7} A frequently used measure is the range of motion, which reflects the mechanical status of the flexor tendons and finger joints.⁸ Other measures score how well or how fast subjects can reach end points in a specific task, such as the Jebsen-Taylor test⁹ or the nine-hole peg test of finger dexterity.¹⁰

Although the above-mentioned assessment procedures may give some insight into the question of whether a movement is impaired, they do not give any insight into *how* the movements are performed. It is argued here that by measuring the kinematic aspects of movement, relevant information is obtained about the control of the movement. The latter is relevant because it has been indicated that the 6-wk period of relative immobilization results in a significant cerebral reorganization, with consequences for the control of finger movements.³

Although a considerable body of knowledge exists suggesting that the kinematics of handwriting movements reflect the underlying motor con-

trol processes,^{11–13} and although the kinematics of handwriting have been employed for studying the effects of neuropharmacologic drugs on fine movements¹⁴ or for assessing the motor aspects of psychiatric diseases,¹⁵ kinematic measures have not been used until now in studying recovery of fine motor control after damage to the peripheral motor system. However, the analysis of kinematic parameters during a movement may uncover normally hidden aspects of performance and may, therefore, be more sensitive to skill improvement and recovery after hand injury.

We hypothesize that analysis of kinematic parameters related to the drawing of a triangle may be relevant to evaluate hand function. We predict that an improved skill level (functional use of the hand) will reflect in an increased drawing speed together with an increased accuracy. The development of such a test may be helpful in the evaluation of cerebral control of hand function and development of future treatment modalities of flexor tendon injuries. A triangle was selected as the target figure because it combines a number of interesting control aspects—namely, accurate multimuscle coordination, planning, acceleration-deceleration sequences, and changes in direction.¹⁶

Experiment 1 was performed to explore whether a standardized skill level could be calculated from the measured kinematic parameters. Experiment 2 explored whether this standardized skill level could be used for the clinical evaluation of changes in the level of hand (motor) performance.

EXPERIMENT 1

The fact that individual subjects draw at different speeds and show substantial individual variance of drawing speed in time complicates the comparison of their data. Therefore, we decided to calculate a *standardized deviation* from the goal figure (triangle) at a *standardized speed* to enable us to compare the performance of subjects drawing at different speeds.

Methods

Subjects

Ten healthy subjects participated in this experiment. Among them were nurses, secretaries, students, and faculty members. Upper-extremity pathology was an exclusion criterion. Table 1 shows the demographic details of all subjects.

Procedure

The measurements took place in a quiet environment with the subject sitting at a table. A piece of paper with an equilateral triangle with 4-cm legs was positioned with the horizontal side up on a

TABLE 1 Demographics of subjects

	Experiment 1		Experiment 2	
	Healthy Subjects	Healthy Subjects	Patients	
<i>n</i>	10	67	12	
Mean age in years (SD)	22 (3)	29 (11)	35 (11)	
Female gender, <i>n</i> (%)	5 (50)	43 (64)	3 (25)	
Lateral preference, <i>n</i> , right hand (%)	10 (100)	65 (97)	9 (75)	

graphics tablet (Ultrpad A3, Wacom Technology Corp., Vancouver, WA). Subjects were asked to trace the triangle with a dedicated tablet stylus for 30.00 secs with the right and then the left hand. The right hand drew clockwise, the left hand counterclockwise. It was stressed that movements of the elbow and shoulder had to be suppressed so that the drawing was performed by the fingers and wrist only. The triangles had to be sharp angled and any rounding of the corners had to be avoided.

The stylus did not leave a visible mark so that the subjects could not see how they performed. Stylus position in time was recorded with OASIS software (KIKO Software, Doetinchem, the Netherlands) on a PC at 170Hz. Raw data were exported and analyzed with custom-made software. The following kinematic parameters were registered: drawing speed (expressed as the number of triangles drawn in 30.00 secs) and average absolute deviation from the “ideal triangle” (mm). Absolute deviation was calculated as the shortest possible

distance between each measured position and the ideal triangle. The software was also capable of registering axial stylus pressure on the tablet, the duration of the pauses in the three corners of the triangles, and the dysfluency of the drawing (i.e., the number of accelerations/decelerations). However, the latter variables were not registered, because a pilot study revealed that stylus pressure was highly variable and did not seem to depend on the level of skill. The same pilot study suggested that variations in pause length and dysfluency could be largely explained by drawing speed.

To determine the relationship between drawing speed and accuracy, ten subjects were asked to draw triangles as accurately as possible at different speeds, arbitrarily chosen as 0.21, 0.28, 0.42, 0.56, 0.69, 0.94, 1.03, 1.42, 1.67, and 2.00 triangles per second. A metronome indicated the speed until the subjects got a hold of the rhythm. When the actual measurement started, the metronome was turned off so that it would not interfere with the measurement (e.g., pausing at the end of one triangle until the next tick of the metronome).

Results

The deviation from the ideal triangle at the different drawing speeds was plotted for the dominant and nondominant hand of each individual separately (Fig. 1a, b). Each series showed a highly linear correlation that was statistically significant (all Pearson correlation coefficients ≥ 0.762 , all *P* values ≤ 0.01 ; Tables 2 and Table 3).

The curves for the nondominant hand tended to run steeper than the curves for the dominant hand. The individual differences between the (healthy) subjects were small. Even when joining

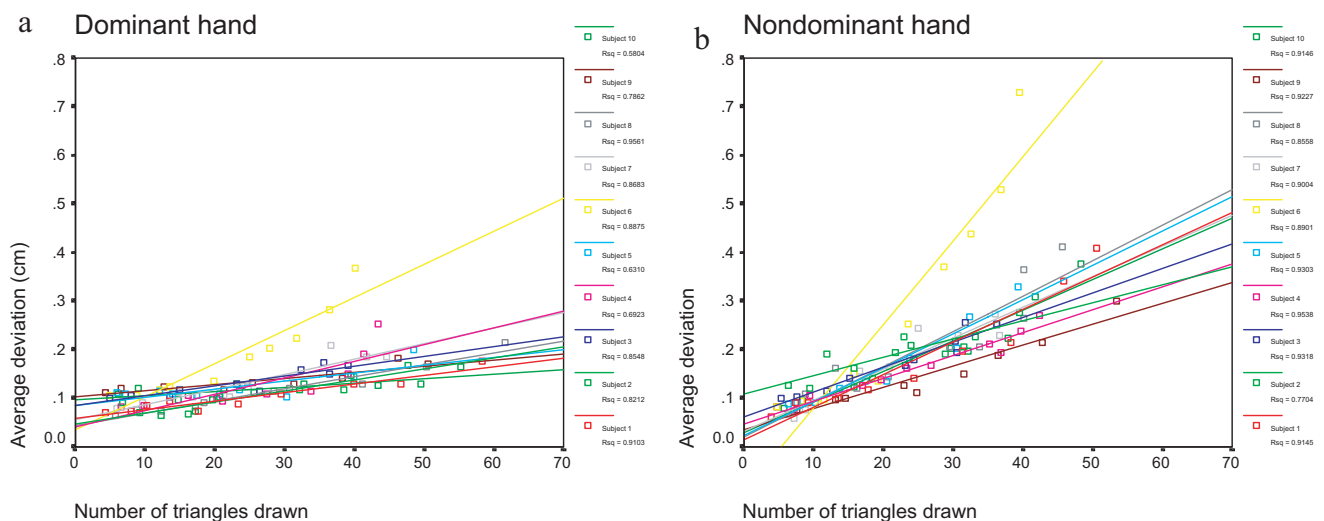


FIGURE 1 Average deviation (mm) of healthy subjects during drawing of triangles for 30.00 secs, plotted against number of triangles drawn in that period (a, dominant hand; b, nondominant hand). Each colored square represents a measurement of one subject. Each line shows the linear correlation between deviation and number of triangles drawn.

TABLE 2 Pearson correlation and *P* values of deviation and drawing speed of all ten subjects, split up by hand dominance; note that a high positive correlation indicates that as speed increases, accuracy decreases

Subject	Dominant Hand		Nondominant Hand	
	Pearson Coefficient	<i>P</i> Value	Pearson Coefficient	<i>P</i> Value
1	0.954	<0.001	0.946	<0.001
2	0.906	<0.001	0.878	0.001
3	0.925	<0.001	0.965	<0.001
4	0.832	0.003	0.977	<0.001
5	0.794	0.006	0.9645	<0.001
6	0.942	<0.001	0.943	<0.001
7	0.932	<0.001	0.949	<0.001
8	0.978	<0.001	0.925	<0.001
9	0.887	0.001	0.961	<0.001
10	0.762	0.010	0.956	<0.001

all data from the dominant hand and separately joining data from the nondominant hand, the correlation remained significant (dominant hand: Pearson correlation = 0.664, *P* < 0.001; nondominant hand: Pearson correlation = 0.776, *P* < 0.001), although not all subjects were equally skilled (Fig. 2).

These findings enabled us to estimate a deviation at a standardized speed, which made it possible to compare the performance of subjects who all performed at different speeds. First, an average formula for the dominant and the nondominant hand was calculated. The formula for the dominant hand is $Y = 0.0022X + 0.0730$ and, for the nondominant hand, $Y = 0.0065X + 0.351$, where *Y* =

TABLE 3 Standardized deviation in centimeters (SD) of healthy subjects during 30 secs of drawing triangles; average values for first and second measurement for dominant/nondominant sides and healthy subjects/patients after flexor tendon injury

	Healthy Volunteers	Patients
First measurement, dominant side	0.106 (0.027)	0.144 (0.033)
First measurement, nondominant side	0.154 (0.041)	0.130 (0.032)
Second measurement, dominant side	0.099 (0.026)	0.116 (0.079)
Second measurement, nondominant side	0.142 (0.031)	0.092 (0.036)

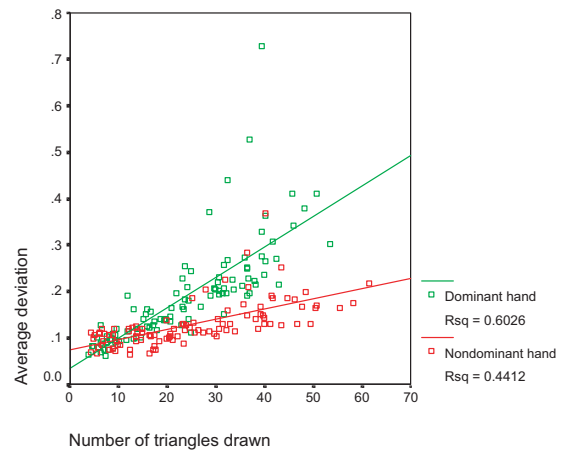


FIGURE 2 Correlation between the deviation (mm) during drawing and the number of triangles drawn in 30.00 secs of the dominant (dark/red) and nondominant hand (light/green). *Rsq*, Pearson correlation coefficient.

deviation (cm) and *X* = number of triangles drawn in 30.00 secs. Figure 2 shows that for the nondominant (less skillful) hand, the curve is not only shifted upwards, but that the whole curve is turned counterclockwise around a pivot point so that absolute inaccuracy of the nondominant hand increases progressively at higher speeds. This pivot point of the two curves can be easily calculated from the above formulas at *X* = 8.8 triangles (and *Y* = 0.092 cm).

In search of a standardized measure that would enable us to compare different measurements and that possesses face validity, we chose to correct the deviation to a standardized speed (arbitrarily chosen as 20 triangles per 30.00 secs). Assuming that a change in skill leads to a change in speed–accuracy with the same pivot point (8.8 triangles and a deviation of 0.092 cm), a standardized deviation can be estimated.

For each individual, a speed–accuracy formula can be estimated as a straight line following the formula:

$$Y = a \cdot X + b$$

where *Y* is the deviation, *a* is the slope, *X* is the drawing speed, and *b* is the constant. To calculate the deviation (*Y*) at a standardized speed, the formula simply becomes:

$$Y_{\text{STANDARDIZED}} = a \cdot X_{\text{STANDARDIZED}} + b$$

with $X_{\text{STANDARDIZED}} = 20$ triangles. *a* can be calculated as follows:

$$a = \frac{Y_{\text{MEASURED}} - Y_{\text{PIVOT}}}{X_{\text{MEASURED}} - X_{\text{PIVOT}}}$$

with $Y_{PIVOT} = 0.092$ cm and $X_{PIVOT} = 8.8$ triangles drawn in 30.00 secs (calculated before). B is calculated as:

$$b = Y_{MEASURED} - \frac{Y_{MEASURED} - Y_{PIVOT}}{X_{MEASURED} - X_{PIVOT}} \cdot X_{MEASURED}$$

so that:

$$Y_{STANDARDIZED} = \frac{Y_{MEASURED} - Y_{PIVOT}}{X_{MEASURED} - X_{PIVOT}} \cdot X_{STANDARDIZED} + Y_{MEASURED} - \frac{Y_{MEASURED} - Y_{PIVOT}}{X_{MEASURED} - X_{PIVOT}} \cdot X_{MEASURED}$$

Filling in the above-mentioned values for $X_{STANDARDIZED}$, Y_{PIVOT} , and X_{PIVOT} , together with the experimental values found for $Y_{MEASURED}$ and $X_{MEASURED}$, leads to a standardized deviation $Y_{STANDARDIZED}$. This standardized deviation can be interpreted as the deviation as if the subject would have drawn at a speed of 20 triangles in 30.00 secs. To improve precision, only drawing speeds higher than the pivot should be selected. In our case, we chose a speed of more than 10 triangles per 30.00 secs as the cutoff point.

EXPERIMENT 2

Methods

Subjects

In total, 12 patients and 67 healthy subjects participated in the experiment. The healthy subjects consisted of nurses, secretaries, students, and faculty members. Upper-extremity pathology and participation in experiment 1 were exclusion criteria.

Patients with isolated zone II finger-flexor-tendon injury were eligible for inclusion if they were between 18 and 65 yrs of age, referred to our clinic for tenorrhaphy, and fit for our standard after-care protocol. This protocol consists of 6 wks of relative immobilization. Four weeks after surgery, the use of the splint is reduced, and placeholder exercises are performed by the patient for 2 wks. Only lesions on the dominant side were included, to prevent the data from being contaminated by influences of laterality on hand skills. Fractures, nerve damage, neurological disorders, and preexistent pathology of the upper extremity were exclusion criteria. The present study was approved by the local medical ethics committee, and all included patients gave their written informed consent. Table 1 shows the demographic details of all subjects.

Procedure

The procedure was identical to that in experiment 1, only now subjects were instructed to draw as quickly and as accurately as possible. The healthy subjects were measured twice with a 2-wk

interval. The patients were measured immediately after the end of the splinting period. This measurement was repeated 2 wks later, whereas a third measurement was performed after a period of 6 wks of active use of the hand. Range of motion of all finger joints of patients were recorded at each visit according to the conventions of the American Society for Surgery of the Hand.¹⁷

The standardized deviation was calculated using the formula as determined in experiment 1:

$$Y_{STANDARDIZED} = \frac{Y_{MEASURED} - Y_{PIVOT}}{X_{MEASURED} - X_{PIVOT}} \cdot X_{STANDARDIZED} + Y_{MEASURED} - \frac{Y_{MEASURED} - Y_{PIVOT}}{X_{MEASURED} - X_{PIVOT}} \cdot X_{MEASURED}$$

The ranges of motion of all finger joints were also measured and expressed as total range of motion.

Analysis

The results of the healthy subjects were entered in a multivariate analysis of variance, with gender and age as covariates. Furthermore, the results of the first measurement were compared with the results of the second measurement, 2 wks later.

Sensitivity of the task to changes in hand skills was explored in the healthy subjects by comparing the results of the dominant hand with those of the nondominant hand (paired t tests). Additionally, the performance of the dominant hand in healthy subjects was compared with those of the dominant (injured) hand in patients with flexor tendon lesions after 6 wks of dynamic immobilization (Mann-Whitney test). The last performance (12 wks post-operatively) of the dominant (injured) hand in patients was compared with that of the second measurement of healthy subjects (Mann-Whitney test). Finally, ranges of motion of the injured hands in patients were compared with those of the uninjured hands (Wilcoxon signed rank test).

Results

Healthy Subjects

Not all data were analyzed, because some measurements did not meet the required drawing speed of 10 triangles per 30.00 secs (see earlier). Standardized deviation was calculated as explained above. Sixty-three of the 67 healthy subjects had at least one valid measurement. Four examples of typical drawings can be seen in Figure 3.

Neither gender nor age significantly influenced deviation on the drawing task ($F(1,35) = 2.4$, $P = 0.07$, respectively $F(1,35) = 2.3$, $P = 0.08$).

The correlation between the two measurements with a 2-wk interval was significant (Pearson

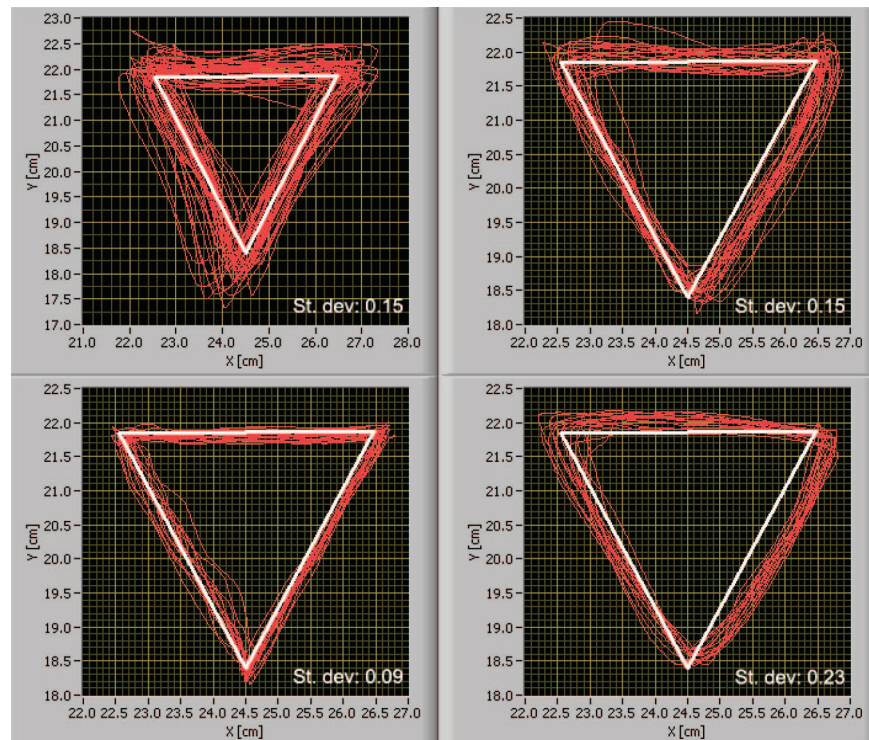


FIGURE 3 Four samples of 30.00 secs of triangle drawing by different healthy subjects. The white triangle is the target that had to be traced. It is difficult to draw final conclusions regarding the skills on the basis of the quality of the drawn triangles only. Whereas the top left sample seems more inaccurate than the top right one, it is also much faster (more triangles drawn). The standardized deviation was calculated, with the formula presented above, resulting in identical scores shown in the right bottom of each drawing. The bottom left sample scores 0.09-cm, and the bottom right, 0.23-cm deviation.

correlation coefficient = 0.909, $P < 0.001$). Healthy subjects performed significantly more precisely during the second measurement (average 5.4% less deviation, $P = 0.002$) than during the first measurement.

The results of the two measurement sessions in healthy subjects showed a significant difference between the dominant and nondominant hand (first measurement: $P < 0.001$, $t = -8.2$, second measurement: $P < 0.001$, $t = -10.9$). The nondominant hand was on average 38% less accurate than the dominant hand.

Patients

When asked about their movement capacities, all patients reported a feeling of clumsiness immediately after the splint was removed. The patients who had worn a splint for 6 wks performed significantly worse with their (formerly splinted) hand than did healthy individuals during both the first and the second measurements ($P = 0.003$, $U = 87$, respectively; $P = 0.043$, $U = 122$). After 6 wks of active use of the (treated) hand, the difference with the hand performance of the healthy subjects had disappeared ($P = 0.513$, $U = 138$).

Compared with the nondominant hand of healthy subjects, the healthy (nondominant) hand of patients showed the opposite effect. Patients performed better with their not-splinted (nondominant) hand after the splinting period than did healthy subjects. This difference, however, was significant only during the second measurement ($P = 0.069$, $U = 130$, respectively; $P < 0.001$, $U = 72$).

Immediately after the splinting period, the fingers of the injured hands in patients had significantly lower ranges of motion than did uninjured hands. This difference persisted after 6 wks of practicing ($P = 0.003$, $z = -2.934$, respectively; $P = 0.011$, $z = -2.547$).

GENERAL DISCUSSION

Results of healthy subjects performing at different speeds showed a strong linear correlation between drawing speed and accuracy meaning that accuracy increases as speed decreases. In addition, all curves of the same side (regarding dominance) are very similar to each other and different from that of the other side. These characteristics enabled us to standardize measurements for speed so that they could be analyzed and compared more easily. The correlation be-

tween two measurements with a 2-wk interval was high. Furthermore, during the second measurement, the subjects generally performed better than during the first measurement. These results indicate that the employed procedure is sensitive for changes in hand skill. This is also supported by the fact that patients performed significantly worse with their injured hand after 6 wks of dynamic splinting than healthy subjects. In contrast, the not-splinted hands in patients were actually better than the contralateral side in healthy subjects. After 6 wks of active use of the (formerly injured) hand, the difference between patients and controls had disappeared. This finding may stress the possible sensitivity of our test to subtle changes: the range of motion of the injured hand was still significantly worse after 6 wks of active use, indicating prolonged impairment, whereas our test already showed improved performance.

Indeed, either by observing task performance or evaluating the end result, no information is gained about how the task was performed, so it might be difficult to conclude which subject had become more skillful during the recovery period. Kinematic analysis of hand movements may assist in evaluating performance of a task.

The calculation of the standardized deviation deserves some more discussion. We are aware that the formula for calculating the standardized deviation is an estimate. However, the mutual influences of drawing speed and accuracy cannot be ignored, and the method described here seems to be sensitive to the level of hand skill. The fact that movement speed affects accuracy has been indicated in numerous articles during the past decades.^{18–22} One way to deal with this problem is fixing either speed or accuracy. Although fixing accuracy in our task might be extremely difficult, it would be easy to fix the speed of performance by using a metronome. This, however, would have led to an unnatural pace for the subjects, which would have influenced their overall performance.^{23,24} Therefore, we chose a more pragmatic solution—namely, a correction for speed, a choice that was supported by the linear relationship that existed between speed and accuracy.

In the present study, *speed* (number of triangles drawn in 30.00 secs) and *inaccuracy* (millimeter-deviation off the line) were used as the main variables. Other studies, mainly analyzing handwriting, have employed other variables as well, such as maximum speed, acceleration, pause length, and dysfluency.^{14,15,25} However, because the variables we selected enabled us to distinguish between dominant and nondominant hands and between healthy subjects and patients, there was no reason to add variables to calculate the stan-

dardized deviation. These variables may be used in the future to fine tune the procedure.

The patients performed less accurately on this task with their injured hand than did healthy subjects. This seems trivial, because the difference in accuracy may also be caused by limited range of motion in finger joints or by effects of general anesthesia.²⁶ The range of motion in the fingers of the injured hands of the patients was indeed significantly worse than the uninjured hands immediately after the splinting period. However, this was still the case after 6 wks of active practice, whereas the significant difference on drawing accuracy after the splinting period had faded after 6 wks of practice. Besides, no significant difference in accuracy was found between patients who underwent the tenorrhaphy under general anesthesia and those who received regional anesthesia. Therefore, we think that limited range of motion or effects of general anesthesia cannot explain the initial decrease in drawing accuracy in our patients.

We assume therefore that the main cause of the decreased hand function after the splinting period is centrally located. As a result of 6-wk period of immobilization and relative disuse of the arm, central neural networks have been reorganized. This is supported by a recent positron emission tomography study performed by our group on patients with tendon injury, which clearly demonstrates a cerebral reorganization as a result of relative immobilization.³ Because this reorganization has a direct impact on the control (and thus performance) of the movements, we have argued that it was necessary to develop an assessment instrument that is sensitive to these performance aspects, that is, that is more sensitive to *how* movements are performed. Although caution remains necessary, we think that the kinematic procedure described here is a step in that direction.

We did not compare our test with other hand function tests such as the Jebsen–Taylor test⁹ or the nine-hole peg test of finger dexterity,¹⁰ because these tests start from a different conceptual level. They are focused on measuring the end result of a movement performance, and not the underlying motor control processes.^{11–13}

The uninjured (nondominant) hands in patients performed better than the contralateral (nondominant) hands in healthy subjects. As the results indicate, this cannot be explained by an *a priori* group difference. We find it more likely that these differences were the results of compensatory use of the uninjured hand during the splinting period. This is supported by the finding that after 6 wks of practicing with the formerly injured hand, no differences in accuracy could be found any longer, compared with healthy subjects.

To our knowledge, the present paper reflects a first attempt to employ a kinematic analysis of hand movements for the assessment of patients with hand injury. This procedure enabled us to assess a thus far-ignored aspect of hand function testing after flexor tendon injury (changes in drawing speed and accuracy). It may be a useful tool to judge treatment procedures on their functional effectiveness.

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